

The Slow X-Ray Expansion of the Northwestern Rim of the Supernova Remnant RX J0852.0-4622

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ABSTRACT

The detection of radioactive decay line of ^{44}Ti provides a unique evidence that the γ -ray source is a young ($< 1,000$ yr) supernova remnant because of its short lifetime of ~ 90 yr. Only two Galactic remnants, Cassiopeia A and RX J0852.0-4622, are hitherto reported to be the ^{44}Ti line emitter, although the detection from the latter has been debated. Here we report on an expansion measurement of the northwestern rim of RX J0852.0-4622 obtained with X-ray observations separated by 6.5 yr. The expansion rate is derived to be 0.023 ± 0.006 % that is about five times lower than those of young historical remnants. Such a slow expansion suggests that RX J0852.0-4622 is not a young remnant as has been expected. We estimate the age of 1,700-4,300 yr of this remnant depending on its evolutionary stage. Assuming a high shock speed of ~ 3000 km sec $^{-1}$, which is suggested by the detection of non-thermal X-ray radiation, the distance of ~ 750 pc to this remnant is also derived.

Subject headings: ISM: individual (RX J0852.0-4622) — shock waves — supernova remnants — X-rays: ISM

1. Introduction

Ten years have passed after the discovery of the supernova remnant (SNR) RX J0852.0-4622. It was uncovered in the southeastern corner of the Vela SNR from the high energy band (above 1.3 keV) image obtained by the *ROSAT* all-sky survey (Aschenbach 1998). The shape is nearly a perfect circle with a large angular radius, Θ , of ~ 60 arcmin. The discovery of this remnant was accompanied by a report of the *COMPTEL* detection of γ -ray

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line emission from ^{44}Ti (Iyudin et al. 1998), suggesting that this new remnant is a young and nearby because of the very short lifetime (~ 90 yr) of ^{44}Ti . Combining it with X-ray and γ -ray data, the age and the distance of this remnant are estimated to be ~ 680 yr and ~ 200 pc, respectively (Aschenbach et al. 1999). So far, most of the follow-up works support the young (less than 1000 yr) age of this remnant (Tsunemi et al. 2000; Iyudin et al. 2005; Bamba et al. 2005). However, the detection of ^{44}Ti line itself has been debated; independent reanalysis of the *COMPTEL* data finds that the detection of this remnant as a ^{44}Ti source is only significant at the 2-4 sigma level (Schönfelder et al. 2000). In addition, Slane et al. (2001) questioned the close distance to the remnant, based on their analysis of *ASCA* data; a larger column density for this remnant than that for the Vela SNR indicated that RX J0852.0-4622 was at a larger distance of 1–2 kpc. The age and the distance are quite curious in the light of the other exceptional natures of this remnant, namely predominance of non-thermal X-ray radiation (e.g., Tsunemi et al. 2000, Slane et al. 2001), existence of an enigmatic central-compact object (e.g., Aschenbach 1998; Kargaltsev et al. 2002), and detection of the TeV γ -ray emission (Aharonian et al. 2007).

If RX J0852.0-4622 is really as young as 680 yr, its large apparent radius of about $60'$ indicates that the proper motion of the shock front would be as fast as $5''.3 (\Theta/60')(t/680 \text{ yr})^{-1}$ per year assuming the free expansion of the shock. The expected motion is large enough to be measured with current X-ray observatories. We perform the first measurement of the shock expansion rate of the northwestern (NW) rim of RX J0852.0-4622 from *XMM-Newton* observations taken over 6.5 yr.

2. Observations and Data Reduction

The NW rim of RX J0852.0-4622 has been observed several times with *XMM-Newton*. Four observations performed in 2001, 2003, 2005, and 2007 are analyzed here. The information of the four observations is summarized in Table. 1. The time difference between the first (2001) and the last (2007) one is exactly 6.5 yr. In this interval, the shift of the undecelerated shock front is expected to be $\sim 35''$. We note that the difference between the Medium filter (for 2001 and 2003 observations) and the Thin1 filter (for 2005 and 2007 observations) has negligible effects in the following analysis, in which we only use high energy events of 1.5–8 keV band. All the raw data were processed with version 7.1.0 of the *XMM* Science Analysis Software (XMMSAS). We concentrate on the data only taken by European Photon Imaging Camera (EPIC) MOS1 and MOS2 detectors, since the spatial resolution of the EPIC MOS is slightly better than that of the EPIC pn detector. We select X-ray events corresponding to patterns 0–12. We further clean the data by rejecting high background

(BG) intervals. After the filtering, the data were vignetting-corrected using the XMMSAS task `evigweight`. We further need to subtract the cosmic X-ray BG and the Cosmic Ray (CR) induced BG at energies above typically 1.5 keV (Arnaud et al. 2001). To this end, we subtract the data set accumulated from blank sky observations prepared by Read & Ponman (2003).

3. Analysis

Figure 1 *left* shows the BG-subtracted *XMM-Newton* hard band (1.5–8 keV) image of the NW rim of RX J0852.0-4622. We can clearly see sharp filamentary structures whose emission is dominated by non-thermal emission (Tsunemi et al. 2000; Slane et al. 2001). These structures mark the current locations of the shock fronts of the NW rim of RX J0852.0-4622. There is a significant X-ray contamination from the Vela SNR along the line of sight. However, the emission is negligible in this hard energy band, since it is believed to be dominated by thermal emission with the electron temperature of below 0.3 keV (e.g., Iyudin et al. 2005).

According to the *XMM-Newton* calibration status report (Kirsch 2007), the absolute astrometric accuracy, i.e., the precision with which astronomical coordinates can be assigned to source images in the EPIC focal plane, is less than $2''$. This value is small enough to detect the expected shift of the undecelerated shock front, $\sim 35''$ per 6.5 yr. We check whether the same position accuracy is achieved in our data. Applying an XMMSAS tool `edetect_chain`, we determine positions of three point sources (P1–P3) indicated in Fig. 1 *left*. Naval Observatory Merged Astrometric Dataset (NOMAD) catalog (Zacharias et al. 2005) identifies several stars as possible optical counterparts for three point sources. We check that the proper motion of the possible optical counter parts themselves are all less than $\sim 1''$ per 6.5 yr. Therefore, we expect to detect the X-ray point sources within circles with radius of $\sim 1''$ in all the four *XMM-Newton* observations. In fact, we find that all the positions determined in our four X-ray data sets (MOS1 and MOS2 separately) are well within $2''$ circles around their mean positions. Therefore, without extra corrections of the coordinates for our data, the absolute astrometric accuracy is achieved to be less than $2''$. In the following analysis, we take account of $2''$ -error for the position accuracy as the conservative systematic uncertainty.

The difference of the 2001 and 2007 images of 1.5–8 keV band is shown in Figure 1 *right*. We can clearly see a black (negative) narrow line running from the northeast (NE) to the southwest (SW) as a sign of the expansion of the shock front in 6.5 yr. Other black or white lines are due to artificial effects such as bad columns or gaps of CCD chips.

Next, we quantitatively measure the shift of the X-ray filament based on one-dimensional profiles across the filament. We select a northern portion of the narrow NW filament as shown in Fig. 1 *left* and *right*, since we find few bad columns there. We slice the area into $2''$ -spaced regions parallel to the filament. The BG-subtracted radial profiles for the four observations are plotted in Fig. 2. In the figure, we clearly see that the peak position of the filament at around $R \sim 115''$ in 2001 is shifted to $R \sim 120''$ in 2007.

In order to quantitatively measure shifts, we also apply the method of calculating χ^2 probability that two observed profiles from different epochs have the same shapes. Let l be the shift parameter, and θ be the angular distance perpendicular to the shock front. Then we calculate the χ^2 value as

$$\chi^2(l) = \sum_{\theta} \frac{[x_1(\theta + l) - x_2(\theta)]^2}{\sigma_1^2(\theta + l) + \sigma_2^2(\theta)}.$$

Here, $x_1(\theta)$ and $x_2(\theta)$ represent the observed count rates in angular distance θ at epochs 1 and 2, and $\sigma_1(\theta)$ and $\sigma_2(\theta)$ represent the uncertainties at each bin. The minimum for $\chi^2(l)$, χ_{\min}^2 , is around 39, since we sum 40 bins roughly around the shock front. We shift the radial profile of 2001 and compare the shifted profile with the profiles of 2003, 2005, and 2007. We examine $l = 0'', 2'', 4'', 6'', 8'',$ and $10''$. The $\chi^2(l)$ -values as a function of l are shown in Fig. 3. In the figure, three kinds of data points with rectangular, circular, or triangular marks are, respectively, responsible for three cases in which we focus on different two epochs, i.e., 2001-2003, 2001-2005, and 2001-2007. We find that χ_{\min}^2 occurs at $l = 0'', 4'',$ and $6''$ for each two-epoch of 2001-2003, 2001-2005, and 2001-2007, respectively. Using the criteria of $\chi_{\min}^2 + 2.7$, we can determine the values of the shifts less than $2''$, at 90% confidence level in all the cases. With taking into account the systematic uncertainty, we derive the shifts of the X-ray filament in 2003, 2005, and 2007 from 2001 to be $0 \pm 2'', 4 \pm 2'',$ and $6 \pm 2''$, respectively. These values lead us to calculate the proper motion to be 0.84 ± 0.23 arcsec yr $^{-1}$, assuming the constant velocity of the shock front in the four observations. Then, the expansion rate is calculated to be 0.023 ± 0.006 % yr $^{-1}$.

3.1. Discussion and Conclusion

Assuming that the shock speed has not decelerated (i.e., the free expansion of the shock), a rigid upper limit of the age for RX J0852.0-4622 is calculated to be 4300 ± 1200 ($\Theta/60'$)($\mu/0''.84$ yr $^{-1}$) $^{-1}$ yr, where μ is the proper motion at present. Table. 2 summarizes expansion rates, ages, velocities of the forward shock v , and expansion indices m for several SNRs, where m is defined as the ratio between the current shock velocity and the mean

shock velocity that is gradually decreases from 1 (free expansion phase) to ~ 0 (disappearance phase) through 0.4 (Sedov phase), 0.3 (radiative cooling phase), and 0.25 (pressure-driven snowplough phase) (e.g., Woltjer 1972). We notice that the expansion rate of the NW rim of RX J0852.0-4622 is about five times lower than those in the Cas A SNR (~ 320 yr), Kepler’s SNR (~ 400 yr), and Tycho’s SNR (~ 430 yr), whereas it is comparable to that determined for the NW filaments in SN1006 (~ 1000 yr). Assuming the young currently best-estimated age of 680 yrs, we derive the value of m for RX J0852.0-4622 to be 0.16 ± 0.04 $(\mu/0''.84 \text{ yr}^{-1})(t/680 \text{ yr})(\Theta/60')^{-1}$. This value is similar to that in the Cygnus Loop which is a representative remnant in the further later phase than the Sedov phase. Therefore, the young age of 680 yr is apparently inconsistent with the value derived. In this context, it is natural to consider that RX J0852.0-4622 is not a young SNR but a middle-aged one. In the upper limit of the age of $\sim 4,300$ yr, it is reasonable to consider that this remnant is in no later phase than the Sedov phase ($m=0.4$). Then, we estimate the age of this remnant to be $\sim 1,700$ ($m/0.4$) yr.

Within the currently accepted theory of diffusive shock acceleration, non-thermal synchrotron radiation in the X-ray band requires a high shock speed, $v \sim 3,000 \text{ km sec}^{-1}$ (Uchiyama et al. 2003; Zirakashvili & Aharonian 2007). Such a high shock speed is actually derived about other four SNRs with non-thermal X-ray radiation (see Table. 2). With the derived proper motion of the shock front, the distance to the remnant, D , is obtained as $D \sim 750$ $(v/3000 \text{ km s}^{-1})(\mu/0''.84 \text{ yr}^{-1})^{-1} \text{ pc}$. Although the distance to this remnant is also highly uncertain, our low expansion rate measured supports a relatively distant value within the suggested range of ~ 0.2 to $\sim 1 \text{ kpc}$ (Iyudin et al. 1998; Ashchenbach et al. 1999). Since our distance estimation relies on only an assumption of the shock speed, which has theoretical and observational bases, we believe that our value is the most reliable one so far, and thus allow more conclusive discussion about the nature of this remnant, e.g., the origin of the TeV γ -ray emission (Aharonian et al. 2007).

We have estimated the age of this remnant to be 1,700-4,300 yr, which is at least 2.5 times larger than the previously estimated age of 680 yr. The new age determined here critically affects the estimation of the initial amount of ^{44}Ti ; it must be about 10,000 times of that assumed in the paper which reported the *COMPTEL* detection of the γ -ray line at 1.157 MeV from ^{44}Ti associated with this remnant (Iyudin et al. 1998). In addition, we should note that the distance estimated here is about four times that derived in the paper, which requires about 16 times larger initial amount of the ^{44}Ti than that assumed in the paper. As a result, the initial mass of ^{44}Ti is estimated to be a few solar masses, using the γ -ray line flux derived by *COMPTEL*. Such a large amount of ^{44}Ti is far from reality; at least four orders of magnitude larger than that expected in nucleosynthesis models (Theilemann et al. 1996; Rauscher et al. 2002). Therefore, it is very likely that the *COMPTEL* detection

of the γ -ray line at 1.157 MeV around RX J0852.0-4622 has no relations to the decay line from ^{44}Ti associated with this remnant.

Finally, we note a possibility to explain the current low expansion rate without any modifications of the age of this remnant: the forward shock recently encountered a dense interstellar medium (or a cloud) in the NW rim and was rapidly decelerated. If such an interaction really occurred, it would be a very recent event so that it did not modify the nearly perfect circular shape of this remnant. Also, a rapid and strong deceleration of the shock would cause a reflection shock near the forward shock. A filamentary structure somewhat distant (about $2'$) behind the forward shock (see, Fig. 1 *left*) is suggested to be a hint of the reflection shock. However, based on the radial profile of the filament obtained by *Chandra* (see, Fig. 2 in Bamba et al. 2005), this suggestion is unlikely and there is no other implications of the reflection shock. Although we can not still completely exclude the possibility of such a rapid deceleration, we think that more straightforward interpretation of the current slow expansion is simply because this remnant is relatively old. Further expansion measurements of the other rim of this remnant will clearly reveal which hypothesis is at work.

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REFERENCES

- Aharonian, F., et al. 2007, *ApJ*, 661, 236
- Arnaud, M., Neumann, D. M., Aghanim, N., Gastaud, R., Majerowicz, S., & Hughes J. P. 2001, *A&A*, 365, L80
- Aschenbach, B 1998, *Nature*, 396, 141
- Aschenbach, B., Iyudin, A. F., & Schönfelder, V. 1999, *A&A*, 350, 997
- Blair, W. P., Sankrit, R., & Raymond, J. C. 2005, *AJ*, 129, 2268
- Iyudin, A. F., et al. 1998, *Nature*, 396, 142
- Iyudin, A., F., Aschenbach, B., Becker, W., Dennerl, K., Haberl, F. 2005, *A&A*, 429, 225
- Kirsch, M. 2007, XMM-EPIC status of calibration and data analysis, XMM-SOC-CAL-TN-0018, issue 2.6
- Hughes, J. P. 1999, *ApJ*, 527, 298
- Hughes, J. P. 2000, *ApJ*, 545, L53
- Kargaltsev, O., et al. 2002, *ApJ*, 619, L163
- Koralesky, B., Rudnick, L., Gotthelf, E. V., & Keohane, J. W. 1998, *ApJ*, 505, L27
- Rauscher T., Heger, A., Hoffman, R. D., and Woosley S. E. 2002, *ApJ*, 576, 323
- Read, A., M., & Ponman, T. J. 2003, *A&A*, 409, 395
- Schönfelder, V., et al. 2000, *A&AS*, 143, 145
- Slane, P., Hughes, J. P., Edgar, R. J., Plucinsky, P. P., Miyata, E., Tsunemi, H., & Aschenbach, B., 2001, *ApJ*, 548, 814
- Thielemann, F.-K., Nomoto, K., & Hashimoto, M., 1996, *ApJ*, 460, 408
- Tsunemi, H., Miyata, E., Aschenbach, B., Hiraga, J., & Akutsu, D. 2000, *PASJ*, 52, 887
- Uchiyama, Y., Aharonian, F. A., & Takahashi, T. 2003, *ApJ*, 400, 567
- Vink, J., Bloemen, H., Kaastra, J. S., Bleeker, A. M. 1998, *A&A*, 339, 201
- Woltjer, L. 1972, *ARA&A*, 10, 129

Zacharias, N., Monet, D. G., Levine, S. E., Urban, S. E., Gaume, R., & Wycoff, G. L. 2005,
NOMAD Catalog in Vizier Online Data Catalog

Zirakashvili, V. N., & Aharanian, F. 2007, ApJ, 456, 695

Table 1. XMM-Newton observations

Obs. ID	Camera	Instrument Mode	Filter	Obs. Date	Good Time Interval
0112870301	MOS1/2	PrimeFullWindow	Medium	2001-04-25	31.3 ksec
0159760101	MOS1/2	PrimeFullWindow	Medium	2003-06-22	19.5 ksec
0159760301	MOS1/2	PrimeFullWindow	Thin1	2005-11-01	38.0 ksec
0412990201	MOS1/2	PrimeFullWindow	Thin1	2007-10-24	62.6 ksec

Table 2. Physical parameters of several SNRs

SNR Name	Expansion Rate (%)	Age (yr)	Velocity (km sec ⁻¹)	Expansion Index	References
Kepler (mean)	~0.24%	390	4,800 (D/5 kpc)	~0.9	1
Cas A (mean)	~0.20%	350	3,200 (D/3.4 kpc)	~0.7	2, 3
Tycho (mean)	~0.12%	430	3,300 (D/2.3 kpc)	~0.54	4
SN1006 (NW filament)	~0.03%	1,000	3,100 (D/2.2 kpc)	~0.34	5
Cygnus Loop (NE filament)	~0.003%	10,000	180 (D/0.54 kpc)	~0.17	6

Note. — 1: Hughes (1999), 2: Koralesky et al. (1998), Vink et al. (1998), 4: Hughes (2000), 5: Winkler et al. (2003), 6: Blair et al. (2005)

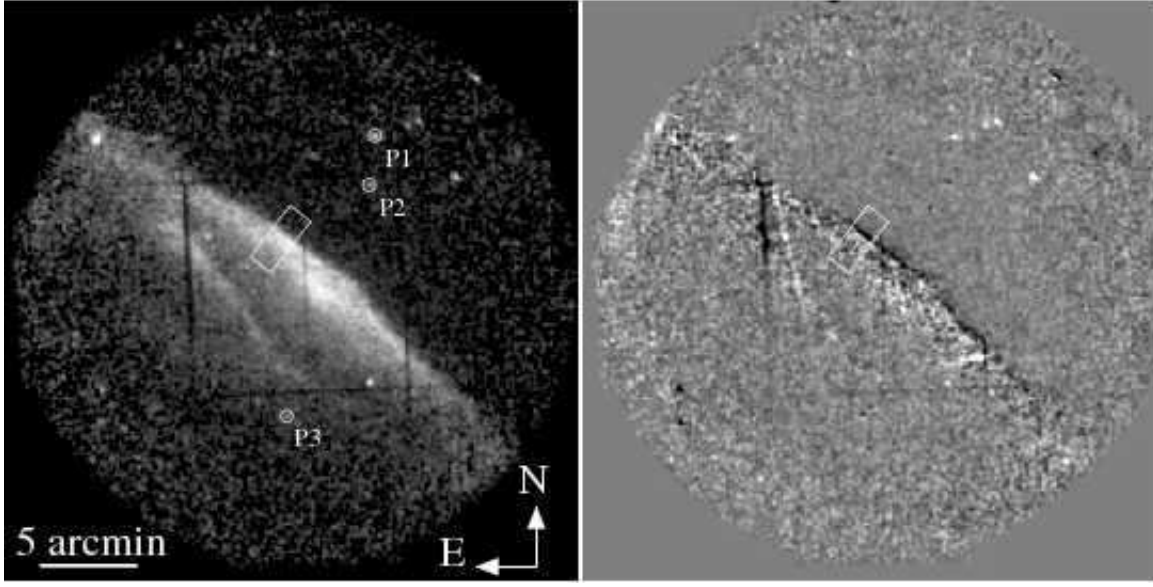


Fig. 1.— *Left:* *XMM-Newton* 1.5–8 keV band image obtained in 2001. The image is binned by $5''$ and has been smoothed by Gaussian kernel of $\sigma = 10''$. The intensity scale is square root. Point source positions which we use to examine the astrometric accuracy are indicated as P1, P2, and P3. We investigate the radial profile of the X-ray filament in the rectangular area. *Right:* Same image but subtracted one obtained in 2007. The intensity is linearly scaled from -1.5×10^{-4} to $+1.5 \times 10^{-4}$ counts sec^{-1} pixel $^{-1}$.

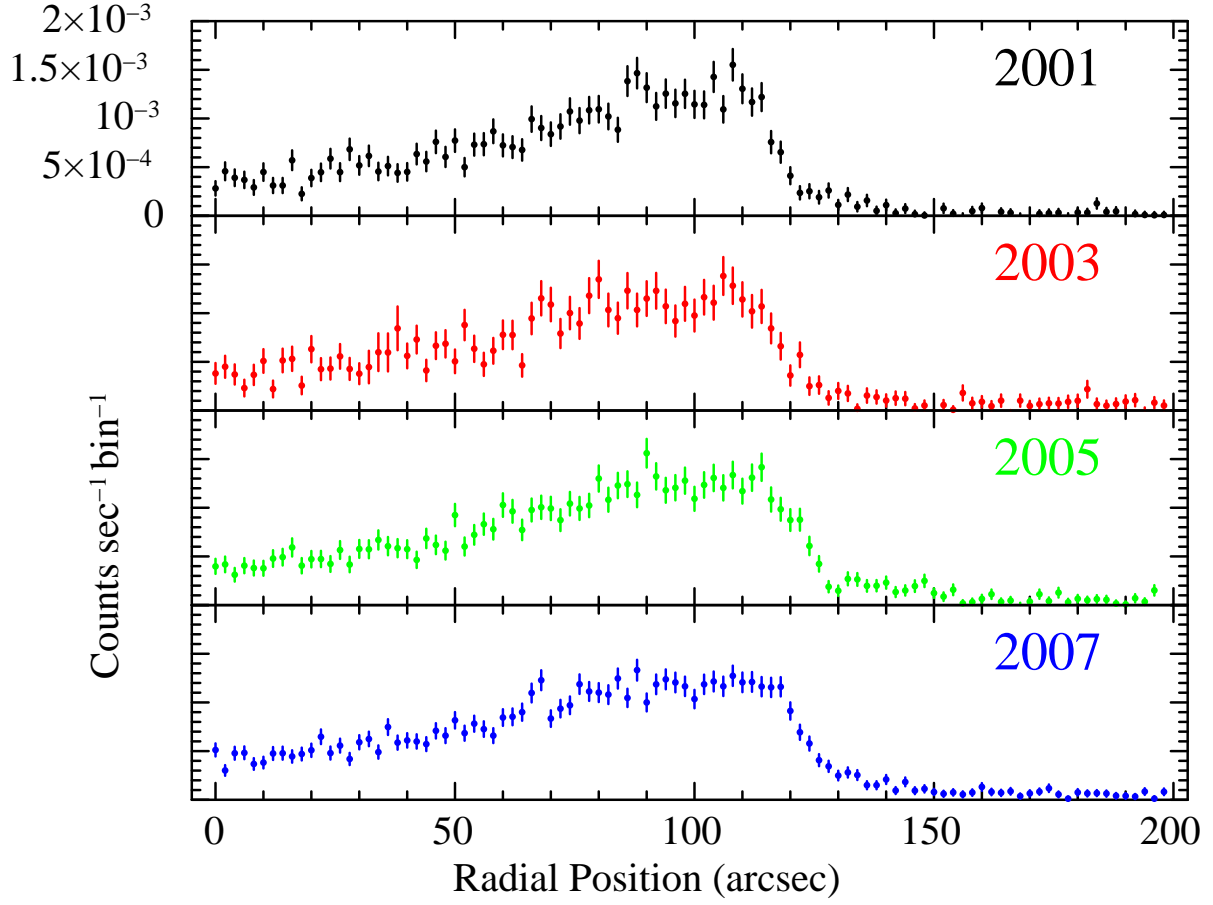


Fig. 2.— Radial profiles at each epoch in the 1.5–8 keV band, binned with a 2'' scale. Four profiles from top to bottom are responsible for the one in 2001, 2003, 2005, and 2007.

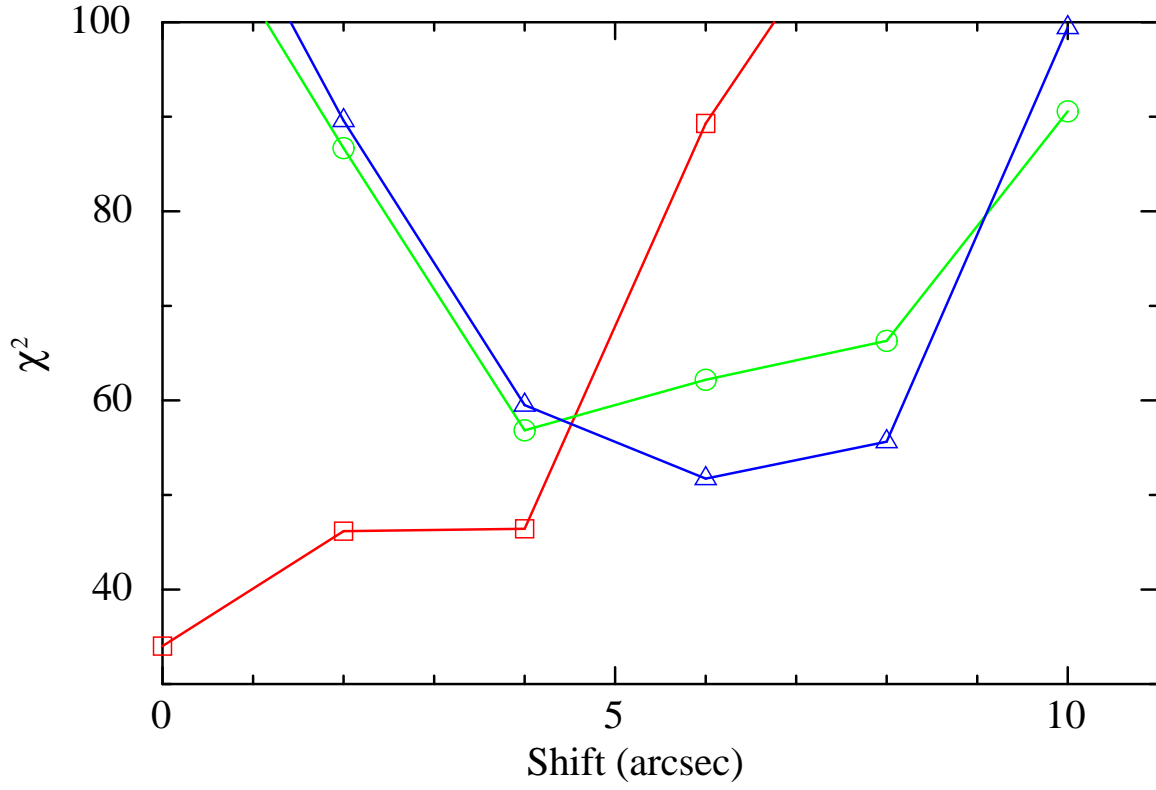


Fig. 3.— χ^2 distribution as a function of the shift parameter, l . Data points with rectangular, circular, and triangular marks are responsible for three cases in which we focus on different two epochs, i.e., 2001-2003, 2001-2005, and 2001-2007, respectively.